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Data challenges in optimizing biochar-based carbon sequestration

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ABSTRACT

Biochar-based carbon management networks (CMNs) offer a means of achieving negative net greenhouse gas (GHG) emissions. Such systems rely on relatively mature technologies for biochar production, distribution and application by tillage; thus, the prospects for near-term scale-up, especially in developing countries with agriculture-intensive economies, are promising. The main technological gap lies in the capability to predict, optimize and monitor the actual climate change mitigation benefits. Computer-aided planning of biochar-based CMNs will be needed to maximize GHG reductions while minimizing any potential adverse environmental impacts. Such models can help decision-makers to understand and optimize the cost/benefit aspects of such systems to accelerate their commercial deployment. This paper gives a brief review of the available scientific literature, and discusses prospective areas for further research to facilitate the large-scale use of biochar as a negative emissions technology (NET).

1. Introduction

In 1977, Dyson [1] suggested that "carbon banking" over relatively short timescales of a few decades is a viable way to delay the adverse effects of climate change, adding further that there "*seems to be no law of physics or of ecology that would prevent us from taking action to halt or reverse the growth of atmospheric CO_2 within a few years if this should become necessary*." He also pointed out that carbon banking through plant growth and soil carbon enrichment can only be considered as an interim strategy, meant to buy time before the effects of a long-term transition from fossil energy can take full effect. Four decades on, the concept of carbon banking remains highly relevant in scientific and policy discourse; some experts now argue that large-scale deployment of carbon capture and storage (CCS) and negative emissions technologies (NETs) will be needed in order to meet the targets of the Paris Agreement [2]. NETs are technologies for achieving net removal of CO_2 from the atmosphere, and include schemes such as direct air capture (DAC), bioenergy coupled with CCS (BECSS), ocean fertilization, anaerobic biomass burial, and biochar-based carbon management networks (CMNs), among others [3]. Although biochar-based carbon sequestration is primarily a soil-based GHG mitigation strategy, it is also sometimes classified as a form of BECCS [4]. Two recent reviews give a comprehensive survey of the status on different NETs, focusing on both technological developments [5] and the techno-economic and risk aspects [6].

Biochar is the carbonized solid co-product of the thermochemical treatment (e.g., pyrolysis or gasification) of biomass which is used for soil enrichment (in contrast to carbonized biomass used as fuel, which is known as charcoal). Biomass feedstocks range from dedicated energy crops to various agricultural or domestic wastes, although from a sustainability standpoint, the land, nutrient, and water requirements of the former are a major disadvantage. On the other hand, residual biomass is often available as an underutilized resource. In fact, improper management of such wastes can lead to CH_4 emissions from anaerobic decomposition or dioxin emissions from uncontrolled burning. Pyrolysis can convert biomass into biochar along with syngas and bio-oil; some of the biomass feedstock can be burned to supply the heat requirements of the conversion process [7]. Majority of the carbon in biochar is recalcitrant (chemically inert), while a smaller fraction is labile (degradable), with the exact proportions being dependent on feedstock and process conditions. In a sustainable bioenergy system, CO_2 emissions from combustion of biomass or its derivatives are completely offset by photosynthesis during feedstock production, although such systems may incur a small carbon footprint from fossil energy inputs (e.g., fertilizer production, biomass transportation) and from agricultural CH_4 and N_2O emissions. Since the carbon in biochar was originally fixed from the atmosphere by photosynthesis, applying biochar to soil effectively gives a negative net flow of CO_2 due to the permanent storage of the stable carbon in the ground [8]. Depending on local conditions, additional beneficial effects can potentially lead to further reductions in system greenhouse gas (GHG) emissions; these effects include changes in soil CH_4 and N_2O releases, lower agricultural carbon footprint due to reductions in fertilizer and irrigation water demand, and fossil energy offsets from the use of the other the co-products (syngas and bio-oil)

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from biochar production [9]. These benefits can be maximized in biochar-based CMNs, which are integrated systems to build up carbon bank in soil, and are structurally analogous to existing agro-industrial supply chains [10]. Woolf and coworkers [9] estimated the emissions reduction potential of biochar-based CMNs at 130 Gt CO_2 eq. until 2100; of this figure, approximately 60% is from direct carbon storage, while the remainder is from the aforementioned beneficial secondary effects. This estimate represents an optimistic upper limit, and does not necessarily take into account local conditions that limit the use of biochar. On the other hand, the annual emissions reduction potential of biochar-based CMNs was estimated by McLaren [3] at 0.9–3.0 Gt CO_2/y, at a cost range of US$8–300/t CO_2.

There has been growing research interest in biochar as a NET. At the time of writing, searching the Scopus database using “biochar” and “carbon sequestration” as keywords yields 982 published documents, 58% (572 documents) of which are from 2015 or later. Among these publications are review papers surveying specific aspects of biochar literature. This paper differs from these recent review articles on biochar for carbon sequestration by focusing on prospective research directions for computer-aided planning and monitoring of biochar-based CMNs. By comparison, Nanda et al. [11] gives a broad review of the biochar literature, including biomass feedstocks, thermochemical processes, biochar properties, and alternative uses (e.g., as charcoal or raw material for activated carbon production). Al-Wabel et al. [12], on the other hand, reviewed the literature focusing on the effects of biochar application on agricultural soil conditions, while Kuppusamy et al. [13] had a narrower emphasis on the risks and benefits of biochar application to soil. The review by Belmonte et al. [10] looked at process systems engineering (PSE) and computer models in the general context of the Water-Energy-Food (WEF) Nexus, with the implicit assumption that data of desired quality has already been acquired *a priori*.

For biochar-based CMNs to become a globally significant climate solution, computer models must be used to plan such systems, to guide their operations, and to monitor or verify actual levels of GHG mitigation. The importance of large-scale, real-time data acquisition for calibrating optimization models is thus a vital aspect that has not been adequately discussed in the current biochar literature. This paper is intended to address this gap by mapping out a futuristic outlook on prospective research directions.

2. Biochar-based carbon management networks

Biochar-based CMNs are a special class of agro-industrial supply chains, and can thus be dealt with using many of the same concepts and tools in the supply chain literature. In such systems, one important constraint is the availability of a supply of biomass within a reasonable geographical proximity to land sinks. In addition to such supply-side considerations, it is also necessary to account for risks that may result from introduction of various biochar-borne contaminants (e.g., salts, dioxins, heavy metals, etc.) to the receiving soil [13]. Such contaminants can potentially cause adverse environmental and health impacts, and may even offset some of the carbon sequestration benefits of biochar application. There is also a practical upper limit to the amount of carbon that can be added to soil [14]. Computer models will certainly be needed in order to plan future large-scale biochar-based CMNs so as to maximize benefits, while keeping risks to an acceptable level [10].

Supply-side considerations make biochar-based CMNs particularly suitable for developing countries with agriculture-intensive economies and abundant biomass. For example, in 2010, the combined agricultural residue available in China and India amounted to 1.4 Gt/y [15]. If even half of this waste biomass is used in biochar-based CMNs assuming typical yields and recalcitrant carbon content, it is possible to achieve 0.5 Gt/y of net CO_2 removal, based solely on direct carbon storage and not even counting secondary beneficial effects. This figure represents 4% of these countries’ emissions (12.7 Gt/y of CO_2 eq.) in that same year [16]. Larger rates of utilization can of course lead to proportionately greater levels of carbon fixation, subject to the availability of suitable land sinks. By comparison, a recent paper estimates the potential of biochar to offset about one-tenth of Scotland's GHG emissions when biophysical limits are taken into account [17]. Despite variations in published estimates, they provide a sense of the scalability of biochar-based CMNs to within an order of magnitude. These results suggest that large-scale use of such systems have the potential to offset a significant fraction of the GHG emissions of many countries. Consideration of limits to biochar application at the sinks may affect these estimates of carbon sequestration potential. Also, the decision on whether to utilize biochar-based CMNs or to consume all of the available biomass as an energy source is not so clear-cut, but is highly context-specific. It will depend on whether larger GHG emissions reduction can be achieved in any given case by application to soil or by offsetting fossil energy with biomass [18].

The fundamental problem in planning biochar-based CMNs is to match biochar sources (i.e., pyrolysis plants) with sinks (e.g., farms or plantations), which is structurally similar to many process integration (PI) problems [19]. The relevant parameters for sources are biochar quality and quantity, both of which are dependent on feedstock type, availability, and pyrolysis conditions. For the sinks, the key parameters are storage capacity (which depends on land area, soil depth and background carbon content) and tolerance to contaminants that may be present in biochar. The characteristics of the sources and sinks may also be subject to temporal variations across seasons. In addition, the desirability of any potential source-sink match depends on proximity, accessibility, and potential interactions between soil and biochar [12]. For the latter interactions, it is in principle possible for thermochemical processing conditions to be controlled to customize biochar properties to the soil conditions at the sinks [20].

Optimization models have been developed to facilitate planning of biochar-based CMNs. For example, a multi-period mixed-integer linear programming (MILP) model was developed for maximizing carbon sequestration in a biochar-based CMN without exceeding soil contaminant limits [21]. This MILP model was later extended into a bi-objective formulation to account for economic factors, as well as secondary sequestration effects due to biochar-soil interactions [22]. In addition to mathematical programming models, other techniques based on process integration (PI) methods [19] have also been demonstrated recently. Examples include pinch analysis [23] and process graphs [24]. Such models provide a useful framework for planning biochar-based CMNs, provided that the required numerical values of key techno-economic parameters are known *a priori*. In practice, the acquisition of data needed to calibrate these optimization models is not a trivial task, but presents a significant, even critical, research challenge.

3. Prospective directions for future research

Unlike many other NETs, the potential benefits of biochar-based CMNs can be achieved with the use of mature technologies. Thermochemical processes such as gasification and pyrolysis are well-developed, and are commercially used for the production of fuel (charcoal) and activated carbon. The handling, storage and transportation of biochar will use infrastructure and vehicle fleets that will be essentially the same as those currently in use for biomass and other bulk solids. Application of biochar to soil on a large scale can be done by mechanical tillage, which can rely on incremental modifications of present-day agricultural machinery. Only the system-level integration of these component units remains unproven, which may account for McLaren's surprisingly low maturity rating of biochar-based CMNs using the technological readiness level (TRL) scale [3]. There appears to be no physical technological barrier to scale-up. Rather, the main stumbling blocks are at the system level, where the challenge is to ensure that the climate change mitigation benefits are realized by the biochar-based CMNs in an economically viable manner. Data-intensive

Table 1
Key features and enabling tools for modelling framework.

Feature	Enabling Technologies and Tools
Spatial and temporal aspects at a resolution level that is relevant to realistic large-scale planning problems.	• Remote sensing • Geographic information systems
Representation of relevant system performance measures as multiple objectives (e.g., carbon sequestration rate, cost effectiveness, etc.).	• Multiple-objective optimization • Multiple-attribute decision-making
Calibration of model techno-economic parameters based on multiple data sources that pertain to both biochar sources and sinks.	• Multivariate statistics • Artificial intelligence • Machine learning • Kalman filter
Model robustness to cope with data uncertainties with a reasonable degree of techno-economic risk mitigation.	• Robust optimization • Stochastic optimization • Fuzzy optimization • Risk analysis and management
Real-time optimization linked to remote sensing for monitoring of operational biochar-based CMNs, coupled with a feedback loop to enable network revamp optimization if it becomes necessary.	• Real time optimization • Control theory • Kalman filter
Appropriate representation of the multi-agent nature of biochar-based CMNs.	• Game theory • Agent-based modelling
Computational tractability	• Multi-resolution models • Pinch analysis • Data compression

modelling techniques will be needed to provide the necessary decision support for planning these systems.

Biochar characteristics can be determined directly by laboratory analysis (e.g., at the site of production), or predicted using mathematical models from biomass properties and processing conditions. On the other hand, sink characteristics are much more difficult to estimate. Soil assays can be performed on samples, but significant variations may occur across the whole area of any potential biochar application site. The effect of biochar application on soil GHG (CH_4 and N_2O) emissions varies widely, depending on biochar properties and soil conditions (e.g., pH, moisture, baseline microbial profile, etc.), thus making it difficult to predict the exact extent of net carbon sequestration achieved by biochar-based CMNs [14]. Transient or dynamic changes in GHG fluxes from biochar addition, known as "priming," [25] further complicate the prediction of overall benefits. The application of biochar to agricultural land also needs to be synchronized with both supply-side (e.g., seasonal availability of biomass feedstock) and demand-side considerations (i.e., farm crop cycles at the application sites). Thus, planning models need to be able to account for these detailed geographic and temporal aspects of biochar CMN operations. Risk analysis techniques also need to be integrated into planning models to account for various parametric or structural (scenario-based) uncertainties [26].

The emergence of modern data analytics offers the prospects of developing new approaches to managing the environmental impacts of man-made systems, including biochar-based CMNs. Wu et al., [27] give a comprehensive survey of the potential of Big Data to address various sustainability issues, based on enhanced capability to monitor, analyze and predict the behavior of large-scale systems. The potential to apply such techniques to facilitate the implementation of Circular Economy (CE) concepts in agro-industrial supply chains was also discussed by Tseng et al. [28]. Biochar-based CMNs as a special class of agro-industrial supply chains [13] can thus benefit from Big Data tools. Available methods range from classical statistical techniques as well as different artificial intelligence (AI) tools such as artificial neural networks (ANNs), swarm intelligence, and fuzzy logic, among others. To date, there has been very sparse literature on such applications. For example, Khare and Goyal [29] applied a combined principal component analysis/hierarchical clustering analysis (PCA-HCA) approach to analyze the effect of the degree of biochar carbonization on soil fertility. Deng et al. [30] developed a least-squares support vector machine (LS-SVM) approach to predict soil-biochar interactions and the effect on nitrogen mineralization. These works focus on local, on-site effects of biochar application, but further extensions can apply at the network level. For example, Latawiek et al. [31] developed a geographic information system (GIS)-based decision analysis approach to rating the suitability of soils in Poland to biochar application. These techniques can potentially be extended for use with more complex, system-level problems.

The geographic scale of biochar-based CMNs will pose significant data acquisition challenges. Remote sensing from satellites [32] or drones [33] has proven useful for monitoring soil and vegetation conditions for other applications; such technologies can thus be useful for data acquisition to determine the potential of specific sites for biochar application. The raw data collected can then be processed using appropriate algorithms, and subsequently used to calibrate optimization models developed for planning biochar-based CMNs [10]. Furthermore, once application of biochar has started, remote sensing can then be used to monitor the sequestration sites to determine any relevant changes in local soil albedo, temperature, and GHG fluxes. Any indication of adverse unintended consequences can then be used to adjust the biochar application plan. Optimal revamp models can be developed for adjusting source-sink matches in such scenarios. Tapia and Tan [34] developed a linear program (LP) for the optimal revamp of CCS networks when CO_2 sinks belatedly prove to be unviable – for example, due to leakage caused by seismic activity. That model can be used as basis for the development of similar approaches for the revamp of biochar-based CMNs. In addition, real-time data from remote sensing can be relayed to the pyrolysis plants to allow corrections in processing conditions (and hence biochar properties) to be made [20].

Another critical aspect is that a biochar-based CMN consists of multiple autonomous decision-making agents. Each biochar source or sink is potentially managed by a private firm motivated to maximize its own profit. Information flow among agents is also restricted due to confidentiality issues. This granularity is often neglected in classical optimization models, which typically assume that there is a single, system-wide decision-maker. By comparison, the behavior of a real multi-agent system is not easily represented using such a framework. Alternative quantitative techniques such as game theory or agent-based modelling (ABM) can be used to reflect the complex interactions that may occur among the system components [35]. Such models then can be used to simulate how various agents that comprise the biochar-based CMNs might respond to policies or incentives designed to encourage investment in carbon sequestration. These considerations point to the urgent need for a research agenda to develop an integrated modelling framework for biochar-based CMNs, similar to those used in enterprise optimization [36]. The key features of such a framework are given in

Table 1, along with key enabling technologies and tools.

Industry 4.0 approaches to enhancing the sustainability of industrial systems have been discussed in the literature [27], along with potential applications in the process industries [37]. The modelling framework described here will in effect be an implementation of Industry 4.0 concepts to biochar-based CMNs. Big Data has been discussed as an important enabling technology for smart farming [38], and can be readily extended to agro-industrial systems that utilize biochar. In particular, new technologies can provide real-time access to data, thus overcoming information asymmetries that are found in conventional agricultural markets. Given the inherently multi-agent nature of these future biochar-based CMNs, improved coordination among decision-makers will be essential for optimizing climate mitigation and economic benefits. In addition to these aspects, biochar-based CMNs also need to be considered within higher-level models that consider a wider range of carbon management strategies, including low-carbon energy technologies, other NETs, and so-called “natural climate solutions” (NCS) [39]. Failure to effectively account for economic barriers has led to the lack of success of other low-carbon technologies such as CCS to reach globally significant levels of deployment [40]. A comprehensive modelling framework can thus provide tools to overcome such barriers to the commercial penetration of biochar-based CMNs.

4. Conclusion

Further research on the provision of tools for computer-aided planning and design of biochar-based CMNs can help to overcome techno-economic risks for investors and thus accelerate scale-up. Essential tools include computer models for system simulation and optimization, as well as remote sensing and GIS to acquire and then manage relevant data on both biomass sources and biochar sinks. With such technologies, there is considerable potential for the optimization of biochar-based CMN operations in real time. In summary, biochar-based CMNs offer the prospect of scalable negative emissions, and are particularly well-suited to developing countries with agriculture-driven economies foundations. Although system-level integration at any commercially significant scale remains unproven, all of the required component technologies are already mature. This feature eliminates a significant barrier which can enable biochar-based CMNs to develop into a viable NET option.

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Declaration on interest

The author declares no conflict of interest.

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